# Qualification of Spacecraft Materials for Use in Harsh Radiation Environments

**Paul B. Willis**
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

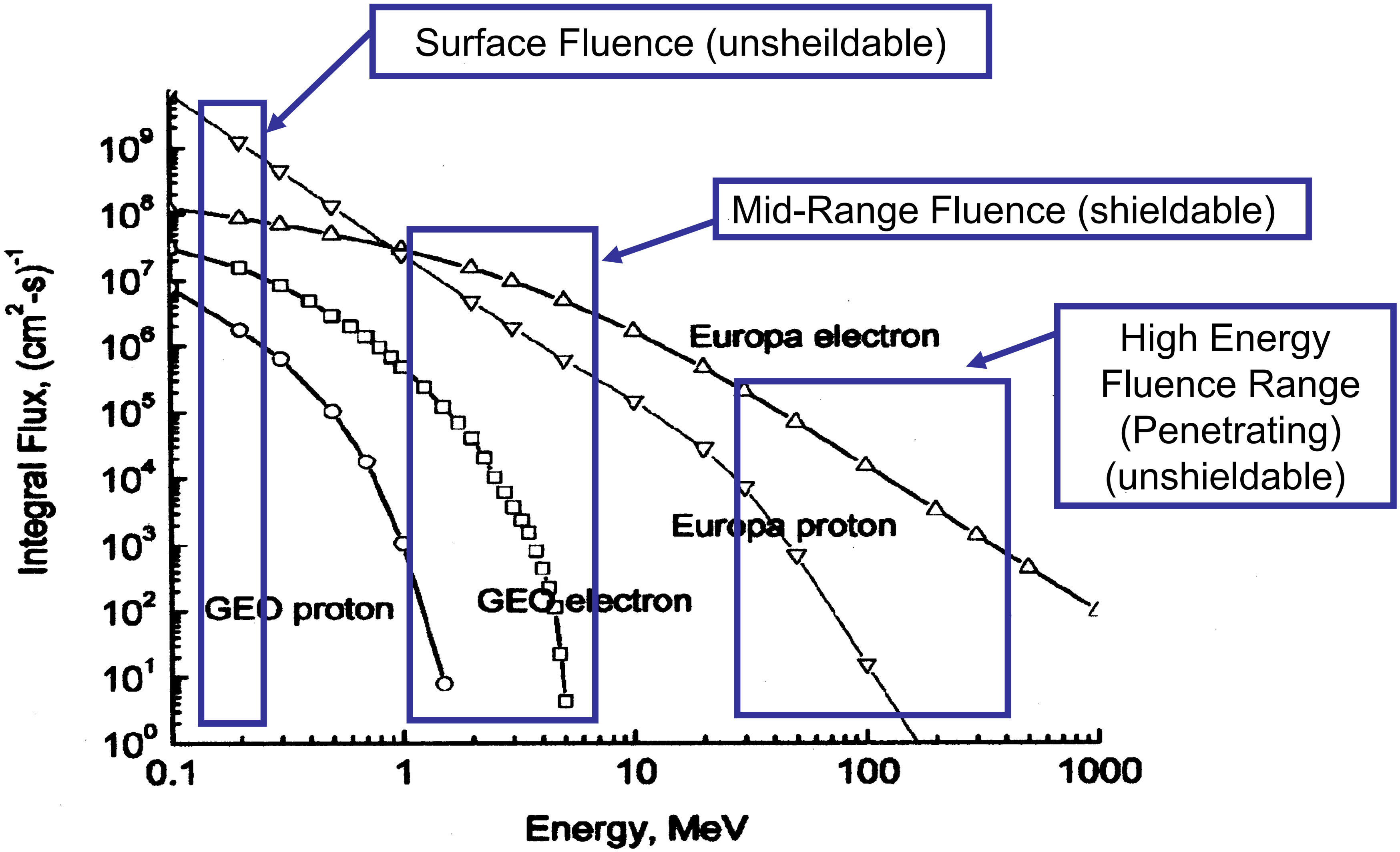
11th ASCE Aerospace Division International Conference
Earth and Space Conference, March 4, 2008

# Harsh Radiation Environments

- **Definition:** For the purpose of this talk, a "harsh radiation environment" is defined as a high flux charged particle environment in space
- Consists of: (a) high surface doses at low energy, and, (b) low doses, but at high energies and long penetration depths
- The Europa Flagship Mission (concept phase) is used as an example
- This mission operates within the intense Jupiter radiation belts
- Current environmental model: GIRE average model with Divine-Garrett pitch angle variation
  - Calculation, plus data from Pioneers 10 & 11 Voyagers 1 & 2, and Galileo
  - Planned mission life, 5 years

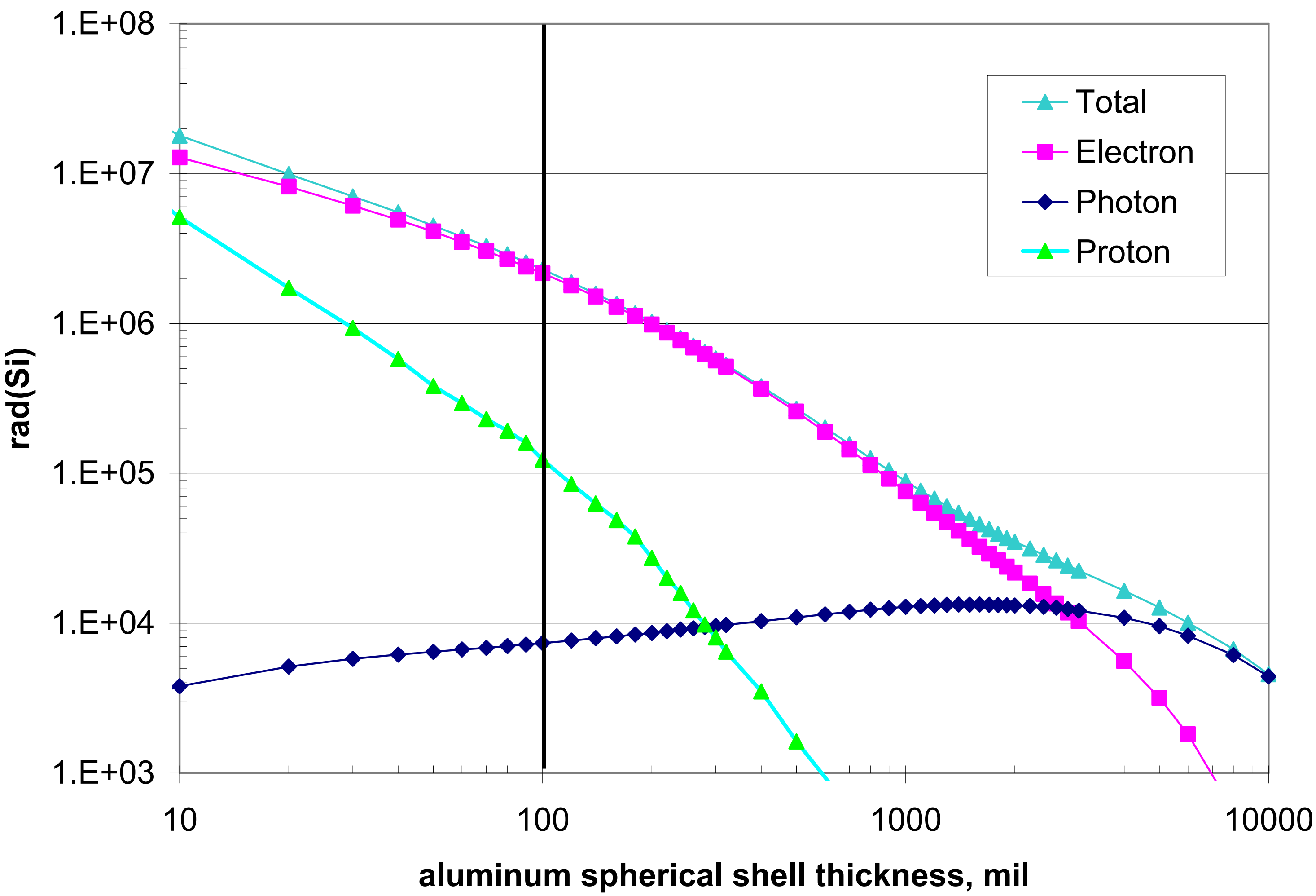
- For Europa, electrons and protons dominate radiation environment
- Electrons up to 1 Gev, protons up to 200 MeV
- Concern: parts and materials survivability
- As "parts" (electronics) are a special field, this presentation concentrates on <u>materials testing</u> and survival
- Europa mission will have radiation exposure higher than any spacecraft flown to date

# Europa Charged Particle Spectra



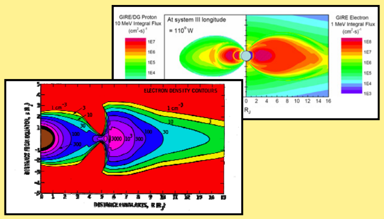
# Europa Dose-Depth Calculation

Dose calculations show that inches of shielding might be required

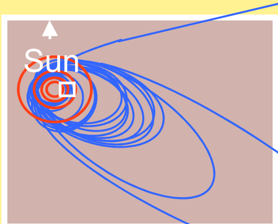


# Europa System Approach

## 1. Define the Environment



• Environment Model*



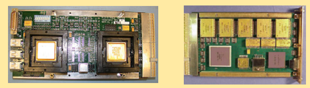

• Trajectory

• Orbital Lifetime

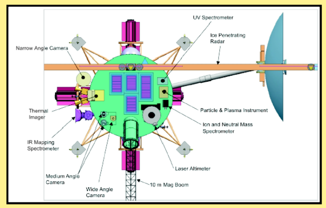
***Multiply by RDF of 2***

## 2. Design for Environment

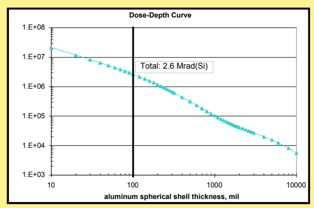
**Radiation-Tolerant & Hardened Parts**



• Parts capability and testing*

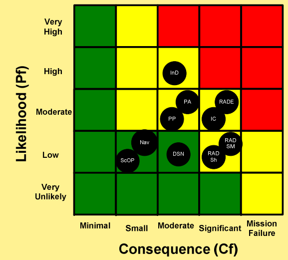


• Configuration and layout

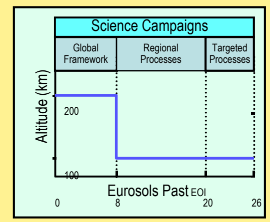



• Transport/Shielding Model*

## 3. Mitigate Risk




- Trade studies and risk analysis (to optimize design and reduce unnecessary margins)*




- Prioritized science collection
- Fault protection
- Contingency plans
- Graceful degradation
- Margins

Conventional Emphasis Areas

Systems Approach Emphasis

*** Areas independently reviewed during Study**

**Radiation system engineering balances performance by trading options with performance risk**

# Radiation Environment Challenge

- In comparison to Earth (GEO), Europa energies are higher by two orders of magnitude; integral fluxes are higher by one order of magnitude for electrons and three orders for protons
- Each particle type has an energy spectrum that dictates the effect and degree of damage as a function of absorbed dose
- Transport codes not verified for many high energy ranges
- Not all particles do the same thing: physics varies as to dose-depth curve, particle type, energy, production of secondary particles, bremsstrahlung (X-rays), etc.
- Effects: Predominant effects are Total Ionizing Dose (TID) and Displacement Damage Dose (DDD), (mainly protons, and electrons over 0.5 MeV)
- Gammas and neutron may be present from Radioisotope thermal generators (MMRTGs)

| DAMAGE | Electrons | Protons | Gammas | Neutrons |
|---|---|---|---|---|
| Ionization | X | | X | |
| Displacement | > 0.5 MeV | X | | X |

- **CHALLENGE:** Test and qualify materials for use when environment cannot be simulated in the laboratory, and not all effects can be predicted

# Principal Radiation Damage Effects

**Ionization Damage**

- Increase in temperature (Non-Ionizing Energy Loss – (heating) "NIEL")
- Polymers: crosslinking, chain scission, embrittlement, outgassing, loss of tensile strength, loss of elongation, destruction of elastomers
- Wire and cable: fracture of insulation, loss of dielectric strength, change in dielectric constant, change in impedance
- Lubricants: loss of lubricity, change in viscosity, outgassing
- Thermal control paints: fracture and discoloration
- Optics and glasses: darkening, internal charging, fracture, fluorescence
- Charge accumulation in dielectrics, possible internal arcing
- Ceramics: may cause conductivity, loss of dielectric strength
- Semiconductors: charge deposition, single event upsets

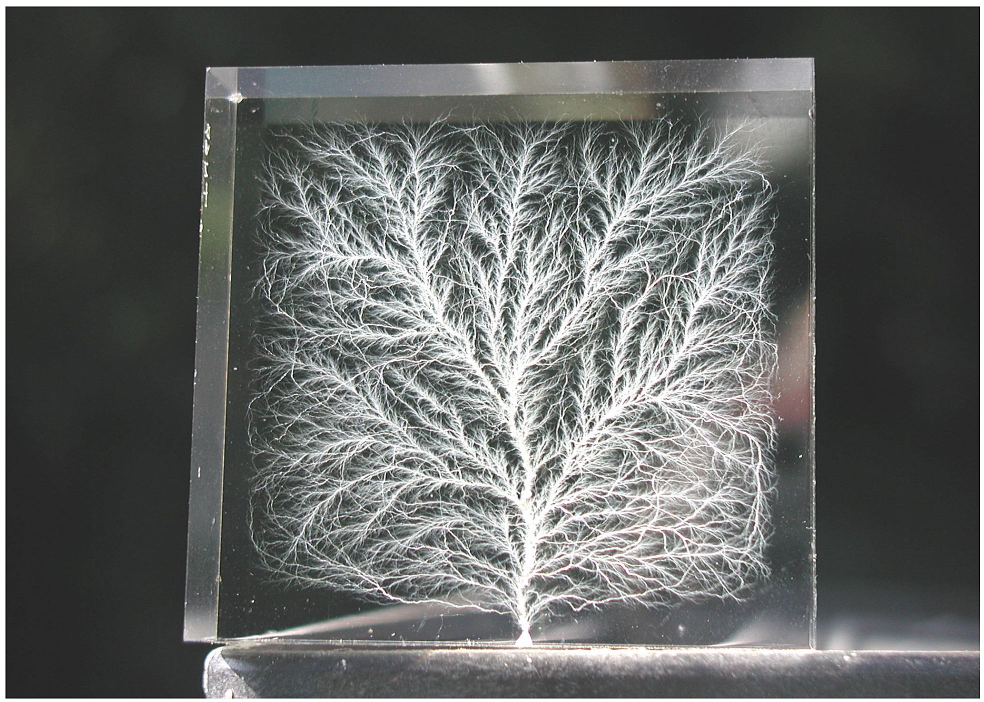
**Displacement Damage**

- Primary effect is damage to semiconductor devices (junction damage)
- Density change, refractive index change and discoloration in glasses
- Fracture and embrittlement of ceramics
- Decrease in tensile strength and yield in some metals
- Damage to permanent magnets

# Internal Charging Effect

- Internal charging can give rise to catastrophic materials breakdown
- A dielectric may trap high speed electrons forming a negative “space charge” region existing at high potential (voltage)
- An insulator may then arc forming a permanent (fractured) low resistance path, and catastrophic materials breakdown
- Electrons also impart conductivity; so <u>lower</u> irradiation rates may be more damaging than very high rates
- Example below: Acrylic, exposed to 4.5 MeV electrons, (Lichtenberg discharge)

60 cm

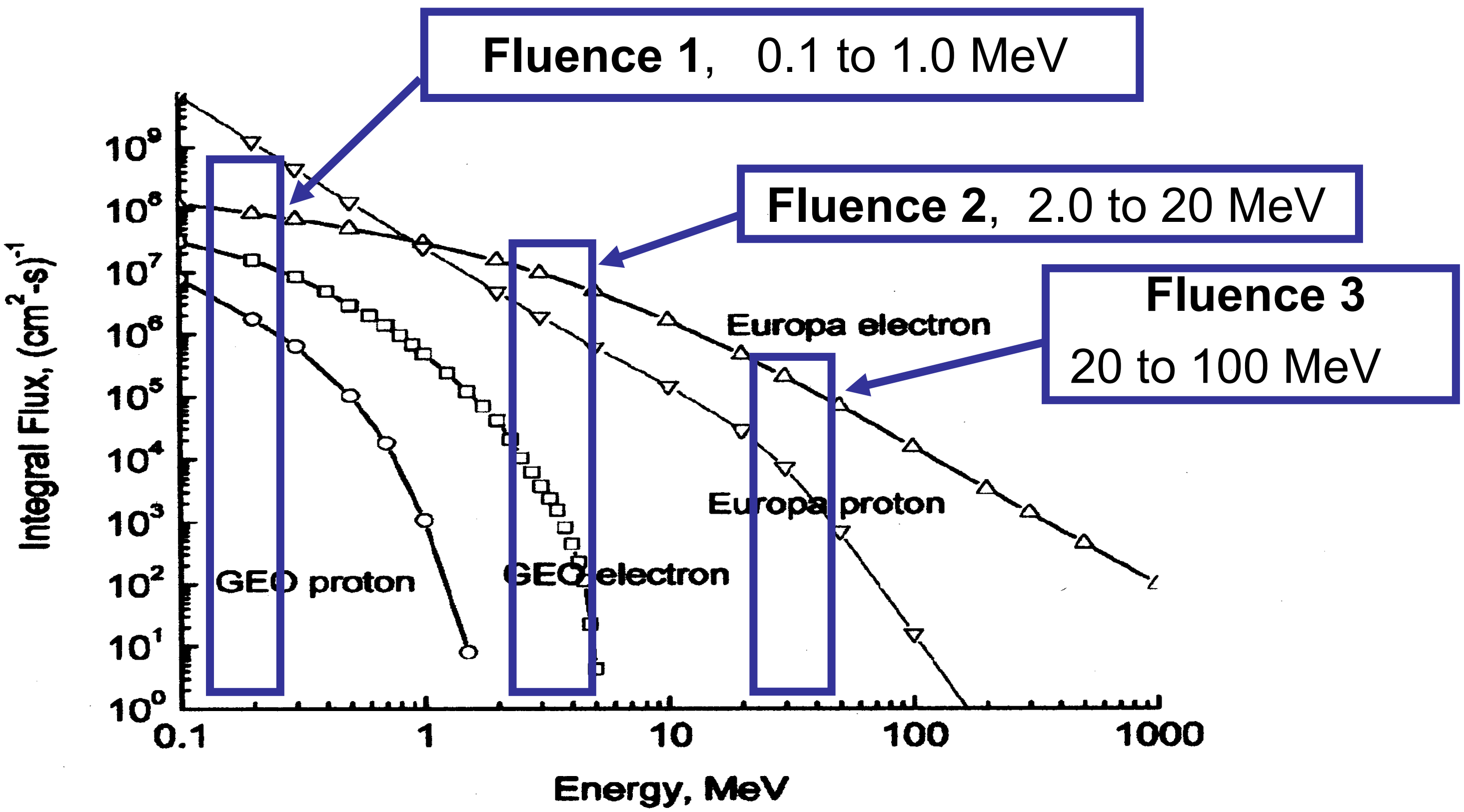


# Group Fluence Testing Approach

- Much of the published materials data is $^{60}Co$ gamma ray exposure (50 years old)
- Although gamma rays are ionizing, damage cannot be realistically simulated due to different dose-depth curves and different physics of interaction
- Dose-depth note: At 1 MeV protons penetrate approximately 1/100 the distance of the electron; gammas penetrate appx. 50 times the depth of the electrons
- Displacement damage (DDD) effects can also not be simulated with neutron exposures due to the mismatch in dose-depth curves
- ***Conclusion: Electrons and protons must be used to determine both ionization and displacement effects as a closer simulation to reality to Europa conditions***
- Group fluence approach: (exposure to discreet energy "bands") may simulate "real" conditions more accurately, and in shorter time
- Physics may not be entirely understood, but may be adequate for screening
- Selection of energy ranges also includes the effects of secondary effects, including: bremsstrahlung radiation, gamma ray production, Compton electrons, pair production, etc.
- Materials stopping powers, and differing penetration depths results in closer match to dose-depth curves

# Europa “Group Fluence” Ranges

- Expose to total Europa mission fluence of electrons and protons using “group fluence” scheme; assumes that all particles in a range have same energy
- Select charged particle sources to provide discreet energies within the group fluence bands. Three main energy bands under consideration



# Rationale for Group Fluence Ranges

**Fluence #1** (0.1 to 1 MeV test energy)

- Highest fluence and largest dose is found in the low energy range
- External materials will all see high flux of low energy particles
- Low energy sources more easily located and less expensive to operate
- Physics well understood; ionization, but little displacement, nuclear capture, activation or induced radioactivity
- Good for screening; if materials/components don't survive the low energy spectrum they are not likely to survive the higher energies

**Fluence #2** (~10 MeV test energy)

- Lower fluence and lower dose at these energies. Damage depends on dose-depth profile in the material
- Sources less commonly located and a bit more expensive to operate
- Physics is now "mixed", resulting in ionization, displacement, defects, and secondary bremsstrahlung (hard X-rays)

**Fluence #3** (~50 MeV test energy)

- Lowest fluence, but highest energy. Largest number of secondary events including neutron spallation, activation, gamma rays
- Most severe condition, despite the lowest dose
- Facilities less common and most expensive to operate

# Possible Charged Particle Sources

**Electrons**

- Electron beam testing for **Fluence 1** range: Typically: (a) Dose controlled by exposure time, (b) energy range: 0.1 MeV to 1 MeV, (c) sources fairly available and inexpensive
- Electron beams for **Fluence 2** range: 2.0 MeV to 20 MeV, and **Fluence 3** range: 20 MeV to 200 MeV
- One possible source identified: Gaertner Radiation Laboratory, Rennsalear Polytechnic Institute (RPI), Troy, New York (covers all group fluence ranges)

**Protons**

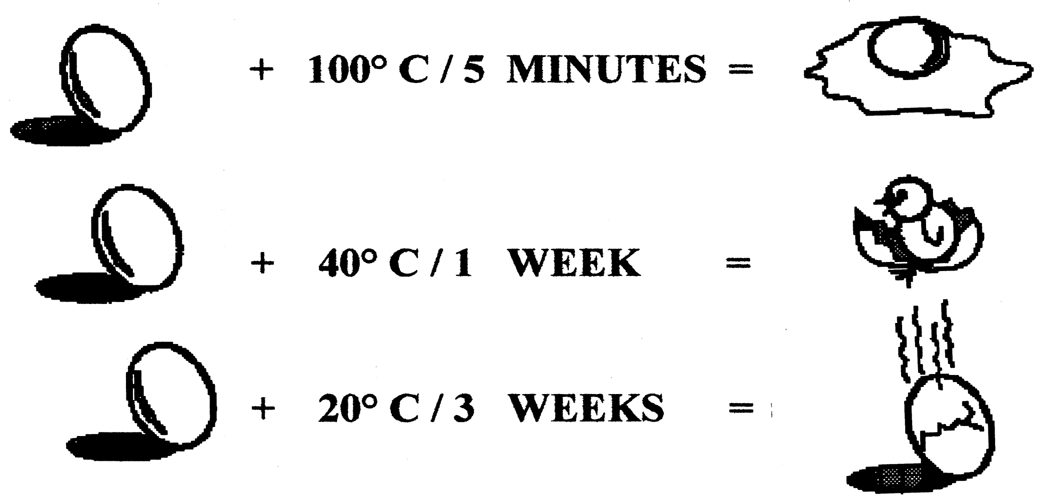
- Possible proton sources for the three fluence ranges are:
- **Fluence 1** range: (1 MeV): Wittenberg University, Springfield, Ohio
- **Fluence 2** range: (10 MeV): Loma Linda University, Loma Linda, CA
- **Fluence 3** range: (50 MeV): University of California, Davis (48 – 67 MeV energy range) and possibly Indiana University Facility (IUCF)
- Protons may apply more to materials susceptible to surface damage; eg. optics, optical coatings, thermal control surfaces, paints, MLI, etc. that may experience dramatic sputtering, cracking and general erosion

# Group Fluence Benefits

- Uses the same radiation sources as found in the Europa environment
- Separating the natural radiation spectrum into three “group fluences” provides a simplified approach that makes practical testing possible
- “Group fluence” approach does not equal reality, but is available, affordable, practical and provides a useful method for screening
- Clear failures and viable components and materials may be identified early in the selection process
- Cost effectiveness: expose to low energy electron testing first to identify non-survivors
- Sets of specimens can be used for each type of exposure, with one last set that is exposed to all conditions sequentially to represent entire mission exposure
- Identifies materials and regions where shielding may be practical

- Materials under consideration: optical glasses, anti-reflective coatings, multi-layer insulation (blankets), thermal control paints, wire and cable, insulations, composites, adhesives, elastomers, lubricants, and Teflon® type materials

# Accelerated Testing - Caveat




**First rule of accelerated testing:**

- Meaningful acceleration is only possible over ranges of time, temperature, rate and energies where the mechanism remains consistent!
- Equal dose does not necessarily result in equal damage (pathway might be different)
- Beware of dose rate effects – is the physics the same?
- Question your results

# Preliminary Findings & Conclusions

- A few “representative” materials were exposed to 4.5 MeV electrons
- Teflon® PTFE and FEP maintained usable properties to 2 x $10^7$ rads; three orders of magnitude better than literature values for $^{60}Co$ gammas in air
- EPDM and silicone rubbers maintained usable properties to 2 x $10^8$ rads; two orders of magnitude better than literature values for $^{60}Co$ gammas in air
- Kynar® and Tefzel® cable insulations began degrading at 2 Megarads; wire and cable insulations may be at high risk
- Kapton® Torlon®, PEEK®, Vespel®, IR grade quartz, sapphire and epoxy-graphite composites all showed no degradation at 1000 Megarad equivalent doses. Highly stable to electron ionizing environments
- Thermal control paints and blankets may be at the highest risk due to extremely high surface fluence
- Insulators may be at high risk due to charge accumulation
- High energy electron exposures in vacuum give very different results than gamma ray exposures in air
- Are fifty year old literature values relevant to Europa missions?

# Survivability Assessment "Roadmap"

1. Define the mission profile (orbits, cruise stage, final destination, etc.)
2. Determine the radiation environment(s)
   - Particle types, energies, and total mission fluence
   - Include all sources: Van Allen belts, RTGs, free space, final destination
3. Tabulate materials and "map" them to known radiation level locations
4. Identify "exempt materials" <u>not</u> at risk of failure
5. Identify materials <u>with</u> a potential risk of failure
6. Determine needed degree of shielding. Include shielding "credit" from other components such as the spacecraft bus, etc ?
7. Use transport code analysis to determine the deposited dose of the particle type in the material of concern
8. Determine survivability, and assess probable risk of failure
9. Correlate risk with spacecraft heritage: have we flown this before in a a similar environment? Is there a history of success / failure?
10. Test critical materials by group fluence method where necessary
11. If the risk of failure is significant: (a) replace the material with one less prone to damage, or (b) add shielding to reduce dose to acceptable level of risk
12. Use analysis tool such as "SAPHIRE" to predict lifetime
13. Remember that the qualification approach is an interdisciplinary process. Ask the experts